1947

Impulse noise in communication receivers and its reduction

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IMPULSE NOISE IN COMMUNICATION RECEIVERS AND ITS REDUCTION

A Thesis

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May 1947

IMPULSE NOISE IN COMMUNICATION

RECEIVERS AND ITS REDUCTION

A Thesis

Submitted to the Faculty of the

Naval Postgraduate School

in

Partial Fulfilment of the Requirements

for the Degree of Master of Science

in Engineering Electronics

by

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Approved: ______________________________

Dean of the Naval Postgraduate School

PREFACE

The material presented in this paper is based partly on a survey of the literature on noise and partly on experience and information acquired in the laboratory working on a specific noise reduction problem.

The entire field of noise is obviously too broad for adequate treatment in a paper of this type. Consequently, emphasis has been placed on impulse noise reduction systems in communication receivers, i.e., in receivers operating in the frequency range of roughly 1 to 20 mcs.

Laboratory work on a noise blanking system was done in the radio interference laboratory of the Lightning and Transients Research Institute, Minneapolis, Minnesota. Development work on the blanking system is being carried out under an Office of Naval Research contract sponsored by the Bureau of Aeronautics.

The author was assigned the task of developing and testing a new type of discriminator for the noise blanking unit based on an original idea by M. Newman of the Lightning and Transients Research Institute. As a result of this development work, a complete blanking unit employing the new discriminator was constructed. It is regretted that insufficient time was available to completely test and evaluate this new system. Rreliminary tests, however, indicated that the scheme has very definite possibilities and warrants further investigation.

Work done by the author at the Lightning and Transients Research Institute was part of the curriculum of the Postgraduate School of the United States Naval Academy, Annapolis, Maryland. The author wishes to express his thanks to Professor M. Newman and other members of the staff of the Lightning and Transients Research Institute for their assistance during his stay in Minneapolis.

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I. INTRODUCTION

1. Definition of Noise

The term "noise" is sometimes broadly used to refer to any disturbance in a radio communication system which is extraneous to the desired signal. This definition would include all kinds of spurious disturbances such as cross talk, images, hum, radar interference, atmospherics, ignition noise, thermal agitation noise, and shot noise. More often the term noise is used to describe only those disturbances which are discontinuous; i.e., disturbances which produce frequency spectrums not confined to a narrow band. This latter definition accurately describes the type of disturbances to be studied, and will be used as the definition of noise in this report.

2. Types of Noise

Noise as defined above is commonly divided into two types, random noise and impulse noise. Random noise is noise due to a large number of closely spaced elemental disturbances occurring at random. Examples of random noise are shot noise in vacuum tubes, noise due to thermal agitation, and corona discharge.

Impulse noise is noise due to a single elemental disturbance or to elemental disturbances separated in time by a period long in comparison with the length of the disturbances. Examples of impulse noise are ignition noise and radar interference.

The elemental disturbances in the above definitions can be, for the purpose of analysis, pulses of short duration. The difference between random and impulse noise then becomes a function of the spacing between pulses, and for this reason it is difficult to classi-

fy all types of noise as either random or impulse. Consider, for example, the atmospheric "static" due to electrical storms. If the noise is produced by a distant thunderstorm, it will be received at high frequencies via the overhead path[1] as a steady "crackling" which can be considered as random noise[2]. This is probably due to the large number of random "crashes" which are being received from an entire storm area. If, however, the thunderstorm is of local origin, the noise will consist of isolated bursts of noise and can be considered as impulse noise.

As will be shown later, the classification of a type of noise as random or impulse may also change due to the alteration of the noise characteristic as it passes through the receiver circuits.

3. Characteristics of Noise

To understand fully the characteristics of noise, it is important to know something about the origin of noise disturbances. The source of most noise is the make or break of voltage or current in an electric circuit. The basic wave form of a switching process is the elementary step or heaviside function. Ideally, most noise can be considered to be made up of combinations of unit step functions; i.e., of a series of short pulses. If the pulses occur at random and are closely spaced, the noise can be classified as ran-

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[1]Potter, R.K., "High Frequency Atmospheric Noise"
Proc. IRE, Oct. 1931

[2]Noise of this type has been found to have very much the same characteristics as thermal noise. See Jansky, K.G., "An Experimental Investigation of the Characteristics of Certain Types of Noise," Proc. IRE, Dec. 1939

dom. If the spacing between pulses is considerable, the noise is classified as impulse. The actual shape or duration of the individual pulses may be altered considerably by the circuit in which they are produced. However, oscillographic study of a great variety of noise sources[3] indicates that the noise which causes radio interference is characterized by pulses having extremely steep wave fronts.

The action of these sharp pulses on the receiver is to shock excite the tuned circuits. The amplitude of the wave train produced will primarily depend upon the steepness of the wave front applied. The frequency of the wave train will be the resonant frequency of the tuned circuit, and the duration of the decaying wave train will be a function of the decrement of the tuned circuit. Appendix I is a mathematical analysis of the shock excitation resulting when a linearly rising voltage is applied to a parallel tuned circuit. The generalized circuit used might be the equivalent circuit of a pentode radio frequency amplifier. The results of this analysis show that the amplitude of the envelope of the wave train is proportional to the slope of the applied voltage in volts per second, and the duration of the wave train is proportional to the Q of the circuit. Since the bandwidth is inversely proportional to the Q of the circuit, the duration of the wave train also will be

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[3] An excellent oscillographic record of noise due to switching and rotating electrical machinery is contained in "Radio Interference Transients Investigation - I and II" by Lightning and Transients Research Laboratory.

inversely proportional to the bandwidth.

In an actual receiver, the large number of tuned circuits complicates the results indicated above. The transient response of a single tuned circuit[4] and a series of tuned circuits in cascade[5,6,7] to a unit step function or impulse has appeared frequently in the literature. The results of these theoretical analyses are verified by the experiments of Landon[8] and Jansky[9] and seem to indicate that the following conclusion can be made: A single impulse applied to the input of a radio receiving device will produce in the output of the receiver a disturbance whose amplitude is directly proportional to the bandwidth, but whose duration is inversely proportional to the bandwidth of the receiver. As indicated previously, the deviation of the slope of the applied disturbance from the ideal perpendicular impulse will reduce the amplitude of the disturbance. However, the slope of the applied pulse must be reduced considerably before shock excitation effects become negligible. As an example, experiments[10] made on a typical communication receiver have shown that the slope of the applied pulse had to be reduced to 0.0175 volts per microsecond in order to reduce

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[4] Jansky, loc. cit.

[5] Landon, V.D. "A study of the Characteristics of Noise" Proc. I.R.E., Nov. 1936

[6] Kallman, H.E., Spencer, R.E., Singer, C.P., "Transient Response" Proc. I.R.E., March, 1945

[7] Sabaroff, S., "Impulse Excitation of a Cascade of Series Tuned Circuits" Proc. I.R.E., Dec. 1944

[8] Landon, loc. cit.

[9] Jansky, loc. cit.

[10] Lightning and Transients Research Laboratory, "Radio Interference Transients Investigation - I", Appendix III

the output disturbance below the background level of the receiver.

The above considerations hold only for noise pulses spaced far enough apart in time so that the wave train produced by one has decayed before the next pulse arrives. If the interval between pulses is reduced so that the wave trains overlap, the situation changes.

This occurs in the case of random noise, where the individual noise pulses are so close together that the resulting wave trains overlap. Since the pulses occur at random, the wave trains will add up at random phase, and the envelope of the resultant will fluctuate in amplitude in random fashion. Since the duration of the wave train produced by each pulse is inversely proportional to the bandwidth, it would seem possible to reduce the duration of the individual wave trains until no overlap occurred by increasing the bandwidth. Theoretically speaking, if the bandwidth was made infinite, random noise could then be treated as impulse noise. Practically, however, infinite bandwidth amplifiers are not available at present, and even if they were, they would not be used in communication receivers which require some degree of selectivity.

The overlapping wave trains produced by random noise alters the amplitude characteristic of the output disturbances. Landon[11] and Jansky[12] have shown experimentally that for random noise the peak amplitude of the disturbance in the output is proportional to the square root of the bandwidth instead of to the first power of

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[11] Landon, loc. cit.
[12] Jansky, loc. cit.

the bandwidth as is the case for impulse noise.

It should be emphasized that many types of noise are combinations of random and impulse noise and, therefore, cannot be classified as either one or the other type. Jansky[13] has also shown that some types of noise produce effects similar to impulse noise for certain bandwidths, but appear to have more of the characteristics of random noise as the bandwidth is narrowed and the individual wave trains start to overlap.

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[13]Jansky, loc. cit.

II. NOISE REDUCTION SYSTEMS

1. Noise Reduction Systems in General

The noise level in a communications receiver is often the limiting factor in determining the performance of a communication system. For this reason, a great deal of time and energy has been expended in developing systems to eliminate or reduce the deleterious effects of noise. One logical approach to the problem is to eliminate the noise at its source. It is entirely possible to eliminate noise produced by electrical equipment by proper shielding and filtering. The job of eliminating all noise of this type is of such magnitude, that it is doubtful if it will be accomplished in the near future. It is also improbable that the noise sources which cause natural static will be eliminated for some time to come.

Another approach to the problem is to use special modulation systems which discriminate against noise. Examples of this are frequency modulation and certain types of pulse modulation. Amplitude modulation using compression or clipping systems to increase the average modulation level might also be considered in this classification.

For the communication frequencies with which this report is concerned, wide band frequency modulation and pulse modulation are, at present, impractical because of the spectrum requirements of these systems. Narrow band frequency modulation, however, appears to have possibilities. Using a deviation ratio (ratio of frequency deviation to maximum modulation frequency) of unity, it is possible to get

significant improvements in weak signal readability over an amplitude modulation system occupying approximately the same frequency spectrum. The reasons for this are not apparent without considering some of the noise characteristics of frequency modulated systems.

Crosby[14] has shown that the improvement over amplitude modulation in signal to noise ratio for random noise is equal to the square root of three times the deviation ratio when the carrier to noise ratio is high. For impulse noise the improvement is equal to twice the deviation ratio. However, when the carrier drops to about 3 or 4 db. above the noise, the improvement for both types noise begins to fall off and is equal to zero when the peak carrier is equal to the peak noise. This is called the "improvement threshold".

For narrow band systems, the "improvement threshold" occurs at lower carrier levels than for wide band systems. This is because the narrower pass band of the narrow band system accepts less noise than the wide band system. Hence, it is possible to get improvement in signal to noise ratios at lower carrier levels with narrow band frequency modulation. Experiments conducted by Crosby[15] have shown that narrow band frequency modulation gives an improvement in readability over amplitude modulation for all values of carrier level. For communication systems in which intelligibility is of primary importance, narrow band frequency modulation seems to have definite possibilities which should be investigated more fully.

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14 Crosby, M.G., "Frequency Modulation Noise Characteristics", Proc. I.R.E., April 1937

15 Crosby, M.G., "Bandwidth and Readability in Frequency Modulation", RCA Review, Jan. 1941

Since most of the communications systems in operation today use amplitude modulation, and the prospects of these systems being replaced overnight by some other system is slight, a study of noise reduction methods in receivers designed for amplitude modulation appears to be worthwhile.

Probably the most effective method of reducing the effects of random noise is to reduce the bandwidth of the receiver to the minimum required for transmission of the intelligence. Since the amplitude of the noise output is proportional to the bandwidth, reducing the bandwidth to the minimmm will give the best signal to noise ratio. For random noise, such as thermal agitation and shot noise, which has its origin in the receiver, the solution lies in proper design of the input circuits of the receiver to obtain the best possible "noise figure"[16, 17].

A large percentage of the man-made noise generated by electrical equipment is high intensity impulse noise, and for that reason a multitude of circuits and systems for the reduction of this type of noise in receivers have been developed and tested. Most of these systems fall into one of the three following categories:
(1) Limiters, (2) Balancing Systems, and (3) Blanking Systems.

The reaminder of this report will be devoted to noise reducing systems included in the above categories.

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[16] North, D.O., "Absolute Sensitivity of Radio Receivers" RCA review, Jan. 1942

[17] Friis, H.T., "Noise Figures in Radio Receivers", Proc. I.R.E., July 1944

2. Previous Work on Impulse Noise Reduction Systems

a. Limiters

The most widely used noise reducing circuit in modern communications is the simple series type peak-noise audio limiter. The reason for the popularity of this limiter is undoubtedly due to the fact that it is extremely effective in reducing impulse type noise and yet requires very few components because of its simplicity. The operation of the series-type and other audio peak-noise limiters is well known and has been described at great length in the literature[18]. For this reason, the discussion of audio limiters will be confined to a mention of a development in audio limiters which shows promise. In most of the standard audio limiters, the level at which the limiting action starts is controlled automatically by the carrier strength. This limiting level is usually adjusted to correspond to a certain percentage of modulation of the incoming signal, usually somewhere between 50 and 100%. The lower the level, the greater the effectiveness in removing noise - also, the more distortion introduced by clipping the modulation peaks of the signal. In an attempt to remedy this situation, it has been proposed that the clipping level be determined, not by the rectified carrier, but by a voltage obtained by rectifying the audio output of the detector. In this way, the clipping level could be made to follow closely the enve-

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[18] Two excellent surveys of limiting systems are:
Bucher, T.T.N., "A Survey of Limiting Systems for the Reduction of Noise in Communication Receivers", RCA Technical Report, TR-876, June 1, 1944
Toth, E., "Noise and Output Limiters", Parts I and II, Electronics, Nov. and Dec., 1946

lope of the audio. This system was first proposed by Pulvari-Pulvermacher[19] in 1934, and more recently interest in circuits of this type has been revived[20,21].

Before leaving peak-noise audio limiters, it might be well to point out the basic limitation of this type of noise reducing system. As has been previously shown, impulse excitation of a tuned circuit produces a wave train whose duration is inversely proportional to the bandwidth. In most communication receivers, selectivity is obtained by using very narrow intermediate frequency amplifiers, and consequently, the duration of the noise wave trains in these stages will be quite long. The noise pulse applied to the audio limiter will be the envelope of the wave train in the output of the intermediate frequency stage. The number of pulses per unit time which the limiter can effectively handle will be limited by the duration of each pulse. Experiments[22] have shown that a square pulse only $\frac{1}{4}$ microseconds long applied to the input of a typical communications receiver produces a pulse 200 microseconds long in the output. If, for a certain carrier level, it is possible to remove one half the signal before intelligibility is lost, the upper limit on the number of 200 microsecond pulses which could be removed by a limiter would be

$$\frac{1}{2 \times 200 \times 10^{-6}} = 2500 \text{ pulses per second.}$$

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[19] U.S. Patent No. 2,144,995, K. Pulvari-Pulvermacher, Jan. 24, 1939
[20] U.S. Patent No. 2,345, 762, G.C. Martinelli, April 4, 1944
[21] Wasmansdorff, C. "Reducing Radio Noise", <u>Electronics</u> Industries, July, 1944
[22] Lightning and Transients Research Laboratory, "Radio Interference Transients Investigation - I", Appendix III

This rough calculation checks closely with the actual performance of limiters. They work quite well when the repetition rate of the noise is low, but somewhere between 2000 and 3000 pulses per second the signal is lost completely.

The above considerations immediately suggest that the limiter be placed in an earlier stage in the receiver. Landon[23] early proposed a system of limiting in the I.F. stages of a receiver. The limiter he used was a current limiter similar to the type used in frequency modulation receivers, and was placed between the third and fourth I.F. stages of the receiver. The R.F. stages and the I.F. stages preceding the limiter were made broad so as to reduce the duration of the noise wave trains. The I.F. stage which followed the limiter was made very sharp to give the required signal selectivity and also to reduce the amplitude of the limited noise pulse. Nicholsen[24] proposed a similar system but used as his limiter a linear detector operating as a convertor.

Theoretically, the R.F. limiter should be placed close to the input of the receiver for most effective results. Practically, however, not much success has been had with R.F. limiters since the difficulty encountered in operating a limiter of this type over a wide range of input levels is considerable. Their use has been confined mainly to low frequency c.w. reception.

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[23]U.S. Patent No. 2,087,288, V.D. Landon, July 20, 1937
[24]Nicholsen, M.G., "A Noise Reducing Circuit", Electronics, Oct. 1936

b. Balancing Systems

Most of the earliest attempts at eliminating noise were systems in which the noise in the desired channel was balanced out by the noise in an adjacent channel. The usual result of such systems was that the noise could be balanced out to some extent in the absence of a signal, but increased to a value greater than without the balancing when a signal was present. Carson[25] showed mathematically that this was true, and his classic paper on the subject has served to discourage many investigators in their quest for a practical balancing system. His analysis, however, was made on the assumption that the noise voltages in the desired channel and in the adjacent channel occur at random phase with each other. The results, therefore, are applicable only to noise which is purely random. Since the envelope of strong impulse noise in adjacent channels is frequently quite similar, it would seem that balancing systems for impulse noise are a distinct possibility.

Many balancing type circuits[26] have been designed for use in the audio stages of receivers. Results obtained are about the same as for peak-noise audio limiters. The limitations of audio limiters discussed above apply, in general, to the audio balancing circuits. In addition, the balancing circuits are a little more critical to adjust. In some cases, however, slightly better results can be obtained by careful adjustment, but this usually necessitates an additional operating control.

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[25]Carson, J.R., "The Reduction of Atmospheric Disturbances", Proc. I.R.E., July, 1928

[26]Bucher, op. cit. and Toth, loc. cit.

A balancing system for use in the antenna input circuits of the receiver was first proposed by Conrad[27]. This device required the use of two antennas, one higher than the other. Each antenna was connected to one side of the primary of the coupling coil of the receiver. A ground was connected to the system by means of adjustable taps at the middle of the primary. The basic idea is that noise of local origin would be picked up equally well by the two antennas and could be balanced out in the primary of the coupling coil. The desired signal, however, would be much stronger in the higher than in the lower antenna and, therefore, would not be balanced out. Many modifications of this scheme have been used including directional antennas, special noise pick up wires, and other balancing methods. The system is especially useful when the source of the noise is known.

c. Blanking Systems

In noise reducing systems of this category, the gain at some point in the receiver is reduced to zero for the duration of the noise pulse. A control element which is responsive to the noise pulse only is used to actuate the gain reducing means.

An early proposal[28] for a blanking scheme used a blocked oscillator to generate the blanking pulse. A noise pulse at the input of the receiver of large enough amplitude would trigger the oscillator and produce a single pulse which would cut off a push

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[27] U.S. Patent No. 1,513, 223 F. Conrad, Oct. 28, 1924

[28] British patent No. 446,634, Ideal Werke Aktiengesellschaft fur Drahtlose Telephonie, May 4, 1936

pull audio amplifier. A long blanking pulse is required in this case because of the long duration of the noise pulse by the time it gets to the audio stage.

Burrill[29] accomplishes the blanking in the first stage of the receiver. He uses two multigrid tubes in push pull as the input stage and cuts them off by applying a blanking pulse to the tubes in parallel. The blanking pulse is generated by a gas triode which is triggered by the noise pulse. The noise pulse in this case is obtained directly from the noise source by means of a pickup line. Blanking in the first stage means, of course, that the blanking pulse need only be a fraction as long as it would have to be if it were used to blank in the I.F. or audio stages. The push pull parallel arrangement prevents any noise from being introduced into the stage by the sudden application of the blanking pulse. The sudden change in plate current in each tube is balanced out in the push pull output coil[30].

In the ideal blanking system, the blanking pulse should be applied just prior to the arrival of the noise pulse. The length of the blanking pulse should be just long enough to cover the noise pulse. Koch[31] accomplishes this timing by inserting a time delay network in the desired signal channel to delay the noise pulse the required amount.

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29 U.S. Patent No. 2,151,740 C.M. Burrill, Mar. 28, 1939
30 See Section III, Part 5 for detailed description of a switching stage.
31 U.S. Patent No. 2,151,773 W.R. Koch, Mar. 28, 1939

A blanking system which has received wide publicity is the noise silencer developed by Lamb[32]. This system utilizes a separate noise amplifier and noise rectifier to produce a negative blanking pulse for one grid of a multigrid tube used in place of the last I.F. amplifier in the receiver. If carefully adjusted, this circuit can give results comparable with that of the series type peak-noise limiter. The increased complexity of this circuit over the series limiter, however, does not seem to warrant its use.

An improved version of the Lamb type silencer is the modified blanking or counter modulation system proposed by Wasmansdorff[33]. A push pull parallel signal amplifier stage as previously described is used as the last I.F. amplifier. A push pull noise amplifier is tuned to one side of the I.F. frequency to reduce the signal component in the noise channel. The audio noise modulation envelope is obtained by rectification and applied to the gain controlling grids of the signal amplifier out of phase with the noise modulation component being amplified by the stage. On the positive noise peaks the gain of the stage will be decreased; on the negative peaks the gain will increase. The result will be a blanking effect on the positive noise peaks and a reduction in the downward modulation of the signal by the negative noise peaks. It is this downward modulation of the signal by the negative noise peaks which makes the Lamb system less effective.

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[32] U.S. Patent No. 2,101,549 J.J. Lamb, Dec. 7, 1937
See also Electronics, March, 1936, page 8, and Russel, W., "Noise Rejection Circuits", Electronics, May, 1939

[33] Wasmansdorff, loc. cit.

III. EXAMPLE OF A BLANKING SYSTEM

1. Operation of Blanking System

A fundamental approach to the impulse noise reduction problem is to reject the noise before it can shock excite the first tuned circuit of the receiver. An example[34] of a blanking system using this approach is shown in figure 1. The unit is designed for insertion between the antenna and the input terminals of the receiver and performs two important functions. First, it shortens any interference pulse to a short pulse of finite length. Second, it shuts off the input of the receiver for the duration of the shortened interference pulse. Figure 10(c) illustrates the blanking action. The effect is that of chopping a hole in the signal carrier. The advantage of such a system is that the portion of the signal lost due to blanking is only a fraction of what would be lost if the noise were rejected later on in the receiver after shock excitation has greatly increased the duration of the original noise pulse.

Briefly, the function of the various stages shown in the block diagram of figure 1 is as follows. The pulse shortening stage

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[34] The blanking system described in this section was developed by the Lightning and Transients Research Institute of Minneapolis, Minnesota under ONR contract N6 ori-230 Task Order One for the Bureau of Aeronautics. Much of the material for this section, including figures 2 and 10(c), was taken from reference 3 in the bibliography which outlines the basic principles and describes the early development models of the system. The rest of the material was obtained by the author during his work in the interference laboratory of the Lightning and Transients Research Institute on an idea by M. Newman for the improvement of the basic system.

shortens the interference to a pulse of finite length. The signal channel (actually the signal plus noise channel) amplifies and delays the shortened interference pulse and signal carrier. The pulse (or noise) channel amplifies the shortened noise pulse and signal, separates the pulse from the signal, and uses it to actuate a blanking pulse generator. The switching stage is an amplifier which is cut off by the blanking pulse just prior to the arrival of the noise pulse. The blanking pulse is made long enough to keep the switching stage cut off for the duration of the interference pulse. Hence, the interference pulse does not reach the input of the receiver and no shock excitation occurs.

2. Pulse Shortening

One of the most important and interesting features of the blanking system being described is the pulse shortening stage. The purpose of this stage is to shorten any long duration pulse to a short pulse of definite duration. The advantage of this is twofold. First, the blanking pulse can be made to have a definite length, thus simplifying the design of the pulse generator. Second, long duration pulses cannot blank out the receiver for any appreciable length of time, which would be the case if the blanking pulse were made to match the length of the interference pulse.

Pulse shortening is accomplished by means of two short circuited transmission lines, one in the grid circuit and the other in the plate circuit of the pulse shortening stage (see 1st 6AC7 in Figure 6 for circuit diagram). For illustration, assume that a long duration rectangular pulse is applied to the first transmission

line. The wave front travels down the line to the short circuit where it is reflected out of phase and cancels all but the initial portion of the pulse. The voltage on the grid will be a shortened pulse whose duration is $2\frac{\ell}{v}$ where l = length of line and v = velocity in line. If there is any loss in the line or if the noise pulse is not rectangular, the cancellation indicated above will not be complete, and to remove any residual the pulse must be applied to a second short circuited line. Figure 2 shows the pulse shortening action on a sawtooth shaped interference pulse. Figure 3 shows oscillograms of the actual operation of a pulse shortening stage. The interference pulse in this case is a differentiated square wave. The repetition rate of the pulse generator was 10 kcs. in (a) and 27.5 kcs. in (b) and (c). The only reason for the increase was to get both positive and negative kicks on a faster sweep. Actually the shape of the shortened pulses was unchanged. The high impedance, high delay cables[35] used were each $\lambda/4$ long at 1.5 megacycles.

Using the above technique, it is possible to shorten a long duration pulse to a short pulse whose length is controlled by the length of short circuit line used. In selecting the length of line, however, the signal repponse must also be considered, inasmuch as the pulse shortening stage must pass the desired signal frequencies as well as the shortened pulse. For the signal frequency at which a cable is a $\lambda/4$ long, the reflected signal will add to the initial signal to give twice the signal response. For two cables of the

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[35] RG-65U spiral core coaxial cable. Characteristic impedance, 1000 ohms; Delay 0.042 microseconds per foot.

same length, the response will be four times that of the original signal. The equation of the response of the pulse shortening cables is $\frac{e_3}{e_1} = 4 \sin \frac{f}{f_1}\frac{\pi}{2} \sin \frac{f}{f_2}\frac{\pi}{2}$, where e_3 is the output voltage, e_1 is the input voltage, f_1 = frequency at which cable No. 1 is $\lambda/4$ long, f_2 = frequency at which cable No. 2 is $\lambda/4$ long, and f = frequency for which the response is being computed. Figure 2 is plotted for $f = 8$ mcs., $f_1 = 10$ mcs., and $f_2 = 10$ mcs. This gives a response of 3.6 for the 8 mcs. signal carrier. The interference pulse has in the meantime been shortened to a total length of 0.1 microsecond.

In order to prevent multiple reflections in the shorted lines, it is necessary to match the lines at their sending ends. It is also desirable to use a matched antenna system to further prevent unwanted reflections. Any extraneous pulses produced by mismatch in the antenna or in the shortening lines will be blanked out in the switching stage, but this represents an unnecessary loss in signal intelligence.

3. Signal Channel

The primary function of the signal channel is to delay the shortened interference pulse just enough to allow the blanking pulse to cut off the switching stage. It must, of course, also pass the desired signal frequencies. The delay required is determined by the relative number of amplifier stages in the two channels and by the speed with which the pulse generator operates. A delay of from 0.5 to 0.75 microseconds is usually sufficient. Either

lumped constant delay lines or high delay coaxial lines can be used to give the necessary delay - providing they have the frequency response to pass both the signal and shortened pulse without undue attenuation or delay distortion.

The frequency response of the entire signal channel must be sufficient to pass all signals in the frequency range of the receiver and also to pass enough of the higher Fourier harmonics of the shortened pulse to preserve its shape. This calls for a video type amplifier since it is desirable that any type of tuned circuit be avoided in the signal channel as a precaution against shock excitation in the blanking unit itself. For example, a unit to cover the broadcast band, 0.5-1.5 mcs., with pulse shortening lines tuned to 1 mcs., would require a frequency response of from 0.5 to 1.5 mcs., to pass signals and a response up to 1 mcs. to pass the 1 microsecond shortened pulse. A video amplifier which was flat up to 1.5 mcs., would then have adequate response to pass both signal and pulse. The low frequency response is not too important as the pulses are of short duration. The amplitude of the pulses would be reduced somewhat, but this is desirable in the signal channel. For a unit to cover from 1 to 10 mcs., the requirements are more exacting. If the shortening lines were $\lambda/4$ at 6 2/3 mcs., the pulse length would be 0.15 microseconds, and the required band pass for the pulse would be 6 or 7 mcs. The video amplifier would have to go up to 10 mcs. to pass the signals, and this would be more than adequate for the pulse.

The only reason for having any amplification in the signal channel is that there is a loss in the delay line and sometimes in the switching stage, and it is desirable to keep the overall gain of the blanking system above unity. This is not essential, however, as most modern communication receivers have more than adequate gain to make up for any small loss in the blanking unit.

In short, the requirements for the signal channel are (1) adequate delay, (2) sufficiently good frequency response to pass all signals covered by the receiver and to pass the shortened pulse without increasing its duration, and (3) enough amplification to give the overall blanking unit a gain of unity or better.

4. Pulse Channel

The two functions of the pulse channel are to (1) separate the pulse from the signal carriers and (2) use the pulse to trigger or actuate a blanking pulse generator.

Removal of the signal carrier from the pulse channel is done by means of a discriminator stage. The discriminator can be made to operate on either the amplitude or rate of rise of the interference pulse. The simplest discriminator is a clipping type amplifier biased so it will be unaffected by any signal carrier, but will pass any pulse of greater amplitude than the strongest signal carrier present. The pulse which is passed is then used to actuate the pulse generator. The disadvantage of this is that only very strong noise pulses will be blanked out if there happens to be a strong carrier present within the pass band of the blanking system.

Another discriminator which shows promise is one which is actuated by the rate of rise instead of the amplitude of the interference pulse. The undesirable effects of shock excitation in a tuned circuit have already been pointed out. In fact, the purpose of the blanking scheme is to reduce shock excitation of the receiver to the minimum. In the discriminator, however, we are interested in rejecting the signal and obtaining only the noise pulse. An ingenious way of doing this is to deliberately shock excite a tuned circuit with the noise pulse. To prevent signal frequencies near the resonant frequency of the tuned circuit from being amplified, a short circuited transmission line which is some multiple of $\frac{1}{2}$ wave length at the resonant frequency of the tuned circuit is placed across the pulse channel ahead of the tuned circuit. This line will act as a short circuit to signals of the same frequency as the resonant tuned circuit, but will allow the pulse to pass on to shock excite the tuned circuit. The wave train produced in the tuned circuit will then be a function of the noise pulse alone. If a high Q tuned circuit is used, the duration of the wave train will be long. The transmission line used to suppress signal frequencies, however, automatically performs the job of shortening the wave train. A noise pulse impressed on the open end of the line will travel down the line, be reflected negatively at the short circuit, and arrive at the open end b seconds later where $b = 2\frac{\ell}{v}$. Since the line is some multiple, n, of $\frac{\lambda}{2}$, the original noise pulse will be followed by its negative in exactly the time equal to n times the period of the tuned circuit.

Hence, after n cycles of oscillation, the tuned circuit will be shock excited again in the opposite phase, and a cancellation of the original wave will result. This cancellation will be quite complete if the decay of the damped wave is small in n cycles.

To further improve the effectiveness of this type discriminator, advantage is also taken of the definite length of the shortened interference pulse. The circuit to be shock excited is "tuned" to the shortened pulse.[36] Figure 3(c) is typical of the shortened pulses which will be impressed upon the discriminator. If the total length of these pulses is equal to the period of the tuned circuit, the oscillations set up by the three vertical parts of the pulse will be in phase and will add up to give a maximum amplitude of oscillation, which is 4 times that due to a single impulse. Appendix II is a mathematical analysis of the actual circuit used in the discriminator. As can be seen from figure 14, the tuned circuit is placed in the plate circuit of a vacuum tube amplifier, and the signal attenuating line is shunted across the grid circuit of the tube. Again it is necessary to properly match the sending end of the transmission line to minimize unwanted reflections. Figure 18 in the appendix is a plot of the shock excited wave in the tuned circuit for $n=4$. Figure 9(b) is an oscillogram of the wave train in the tuned circuit when the pulses

[36]The idea of using a discriminator tuned to the shortened interference pulse is considered the most important feature of a blanking system of the type being described. Credit for the idea is due to M. Newman of The Lightning and Transients Research Institute. Patent applications for a system using this feature are being prepared.

shown in the oscillogram of figure 9(a) are applied to the grid circuit. The shortened pulses in (a) are somewhat distorted in this picture, but the negative reflection of the pulse can be clearly seen.

We now have a device which responds best to pulses of a definite length and which is insensitive to sinusoidal signals. It is only necessary to recover the envelope of the wave in the plate circuit of the shock excited amplifier. This is done practically by means of a rectifier circuit using crystals. The result is a pulse about n times as long as the shortened interference pulse. This pulse can be used to actuate the blanking pulse generator or can be amplified and used itself as the blanking pulse.

The requirements of the pulse generator are that it must be actuated by the noise pulse output of the discriminator and must produce a negative blanking pulse of somewhat longer duration than the shortened noise pulse and be of sufficient amplitude to completely cut off the switching stage. Usually, a 20 or 30 volt blanking pulse is more than adequate for the multigrid tubes used in the switching stage. Figure 9(c) is an oscillogram of a typical blanking pulse.

A type of pulse generator which has been used successfully with the clipping type discriminator is a "one shot" multivibrator. The multivibrator is triggered by the pulse output of the discriminator.

The "tuned" discriminator described above is in effect its own pulse generator. The rectified envelope need only be amplified to give a blanking pulse of the proper amplitude.

The gain requirements of the pulse channel must also be considered. For the clipping type discriminator and multivibrator pulse generator the requirements are not too difficult to meet, since the minimum amplitude of noise pulse which can be detected must be larger than the strongest signal carrier present. If, for example, the strongest signal carrier present is 5 millivolts and the multivibrator is adjusted to be triggered by a 5 volt pulse, the amplification necessary will be 1000. With the tuned discriminator it is possible to detect noises well below the level of the strongest signal carrier. If, for example, the discriminator operates satisfactorily on 20 microvolt noise pulses and a 20 volt blanking pulse is required, the necessary amplification will be 10^6.

5. Switching Stage

The switching stage is probably the most important part of the blanking system. Its purpose is to shut off the input of the receiver for the duration of the shortened interference pulse and thus prevent shock excitation of the receiver. The simplest way of accomplishing this would be to use a multigrid amplifier tube in the switching stage. The signal and pulse from the delay line would be applied to one grid and the negative blanking pulse to another grid. The blanking pulse would cut off the tube and thus prevent the noise pulse from reaching the receiver input. Such a system, however, has the disadvantage that the sudden drop and rise of plate current due to the blanking pulse will produce a pulse of voltage across the plate load which in turn will shock excite the input circuit. To remedy this, two multigrid tubes

(6L7's) are used with their plates connected in push pull to a balanced output coil. The signal and shortened pulse are applied to the No. 1 grid of one tube, and the blanking pulse is applied to the No. 3 grids of both tubes. For signal operation only the one tube operates, but when the blanking pulse is applied, the plate currents of both tubes are reduced to zero. Since the currents in the output coil are in opposite direction, the net change in flux in the coil will be zero, and no voltage will be induced in the secondary because of the blanking action. It is very important that the output circuit of the switching stage be carefully balanced. This requires the use of matched tubes, symmetrical layout of components to prevent unbalance due to stray capacitances, and a Faraday shield between primary and secondary to minimize electrostatic coupling. Figure 10(c) is an oscillogram showing blanking action with good balancing. The coupling coil in this case was self resonant in the broadcast band. Figure 10(a) shows shock excitation of a receiver input without blanking. Figure 10(b) is the same, but with blanking. In this case, the balancing is not perfect, probably because of the fact that coupling coil was self resonant at about 10 mcs., and stray capacities contributed more to unbalance at these frequencies. The same circuit was used in the two switching stages.

The above illustration is given to emphasize the importance of balancing in the switching stages. With proper balancing, the shock excitation at the input of the receiver can be practically eliminated. There is, however, a small amount of noise introduced

by removing part of the signal carrier. It has been shown[37] that the amount of noise due to removal of one cycle of R.F. from the signal carrier is equal to 1/Q times the signal amplitude, where Q is the Q of the resonant circuit upon which the signal carrier is impressed. Since the Q of tuned circuits in communication receivers is usually very high, the noise from this source is almost negligible providing the number of cycles blanked out is kept small. This means that the blanking pulse length should not be made any longer than is necessary to blank out the shortened interference pulse.

6. Performance of Blanking Systems and Comparison with Audio Limiter.

Several laboratory models of the blanking system using the clipping type discriminator and multivibrator have been constructed and tested[38]. One model was built to cover the broadcast band and proved to be very effective in demonstrating the principles of the blanking scheme. This particular model had a rather long blanking pulse (20 microseconds) but still was able to effectively reject up to 10,000 interference pulses per second. Intelligibility tests showed an improvement of 40 db. over operation without the blanking system.

Operation of the above blanking unit disclosed two limitations of the clipping type discriminator - multivibrator pulse generator combination. First, the modulation peaks of strong local broadcast

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[37] Lightning and Transient Research Laboratory, "Radio Interference Rejection at Antenna-I", P. 17

[38] *Ibid.*, pp. 10-20

stations get through the discriminator and trigger the multivibrator unless the discriminator is adjusted to a very high clipping level. When tuned to a weak station this means that the noise peaks could be considerably larger than the signal and yet not be blanked out if they were equal to or less than the amplitude of the modulation peaks of the strongest signal in the pass band of the device. Of course, the system works very well on extremely loud noise pulses; i.e., there is no upper limit to the amplitude of noise pulses which can be rejected.

The second limitation concerns the operation of the multivibrator. As has been mentioned above, the blanking pulse was 20 microseconds long. The shortened noise pulse, however, was only 1 microsecond long, and, consequently, the amount of signal lost due to blanking was many times what it should have been. Shortening the blanking pulse will undoubtedly increase the rate at which noise pulses can be rejected, providing the switching stage can be balanced at the higher rates made possible by the use of shorter pulses. Development work being carried on at present indicates that the upper limit of operation of the clipper-multivibrator system may easily be extended to 30,000 pulses per second and probably much higher.

An example of a blanking unit using the tuned discriminator-pulse generator principle is shown in figure 4. Figure 5 is a block diagram and figure 6 is the schematic diagram. This unit was constructed by the author as part of the development program[39]

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[39] Development of the blanking system is being continued under ONR contract N6 ori-230 Task Order Two for the Bureau of Aeronautics.

to improve the operation of the original blanking scheme.

Referring to the block diagram of figure 5 and the schematic of figure 6, the pulse shortening stage, video amplifiers, cathode follower, delay line and switching stage are almost identical to the circuits used in the demonstration model of the blanking system described above[40]. The entire pulse channel, however, has been replaced by the new discriminator and pulse generator. In the new pulse channel, one half of the 6SL7 is used as a cathode follower, the other half as the tuned discriminator. The 6SK7 is an amplifier which is tuned to the frequency of the oscillations in the plate circuit of the 6SL7. The 1N21B's are used to rectify the wave train to obtain the envelope. The 6AC7 is a video amplifier which amplifies the pulse output of the rectifiers to give about a 20 volt negative blanking pulse.

The signal pass band of the unit was designed to be from 1 to 10 mcs. Originally, the pulse shortening lines were to be $\lambda/4$ at 6.7 mcs., and the tuned circuits in the pulse channel were also to be tuned to 6.7 mcs. It was found, however, that when the cables were cut to give maximum signal response at 6.7 mcs., the length of the shortened pulse produced was considerably longer than the length of line would indicate. In other words, the velocity of propagation in the cable for the sine wave signal was different than that for the pulse. This can be explained in terms of the delay distortion

[40] Lightning and Transient Research Laboratory, "Radio Interference Rejection at Antenna-I", pp. 12-14

in the line. For spiral wound delay lines[41] of the type used, the effective inductance of the line decreases with frequency, and since $\tau = \sqrt{LC}$, the delay also decreases with frequency[42]. If we consider a pulse as a Fourier series of sine wave components, we can readily see how the different components will travel with different velocities in the pulse shortening cable and arrive at the open end of the cable at slightly different times. The result of these slight phase differences will be that the components will add up to give a pulse which has been effectively broadened. The extent of this distortion is illustrated by the performance of the lines used in the blanking unit being described. The maximum response of the line to signal was at about 9 mcs., whereas it was necessary to tune the discriminator tuned circuit to 5.8 mcs. to get maximum response from the shortened pulses. This effect was not noticeable in previous models designed for operation at broadcast frequencies. In extending the range to higher frequencies it will probably be necessary to use special equalized delay lines[43].

The frequency response of the pulse shortening stages and the video amplifiers (including the 6AC7 cathode follower) is shown in figure 7. Although the two pulse shortening lines were the same length, they resonated at slightly different frequencies as is shown

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[41] The only reason for using high delay lines in the pulse shortening lines is to cut down the physical length of the lines.
[42] Kallman, H.E., "Equalized Delay Lines", Proc. I.R.E., Sept.1946 p.648
[43] Ibid., pp. 646-657

by the two peaks in the curve. This is probably due to the different total shunt capacities across the lines in the grid and plate circuits. The other curve in figure 7 is the overall signal response of the unit. The very sharp peak just above 10 mcs. is at the resonant frequency of the primary of the output coil in the switching stage. The high resonant frequency and high Q of this coil probably account for some of the difficulties in balancing which were encountered (see figure 10b). A more judicious choice would have been to make the coil of much lower Q and have it resonate broadly at about 7 or 8 mcs.

Overall operation of the unit can best be illustrated by running through some oscillograms taken at different points. Figure 8(a) shows the 40 microsecond noise pulse applied to the antenna. Figure 8(b) shows the shortened pulse on the first line, and figure 8(c) on the second line. The total length of the pulse in figure 8(c) is about 0.175 microsecond. When observed with a faster sweep speed, these pulses do not look as pretty as the pulses in figures 3(b) and (c). This is probably because of the delay distortion mentioned above. Figure 9(a) shows the amplified shortened pulse and its negative reflection which is applied to the grid of the 6SL7 tuned discriminator. The distortion of these pulses is partly due to the delay distortion in the lines and also partly due to overdriving the last video amplifier. Figure 9(b) shows the waveform on the plate of the 6SL7, and figure 9(c) shows the 20 volt blanking pulse at the plate of the 6AC7 video pulse amplifier which was obtained by

amplifying and rectifying the waveform of figure 9(b). Figure 10(a) shows the shock excitation at the receiver input caused by the amplified shortened pulse of figure 8(c) with no blanking. The "receiver" in this case was actually a Ferris Model 32A Noise and Field Strength Meter and was tuned to 1 megacycle. Figure 10(b) is the same with blanking. The balancing in the switching stage is not perfect in this case. The output of the noise meter, however, dropped 20 db. when the blanking was cut in, indicating a considerable reduction in shock excitation. Listening tests indicate that the amount of noise indicated by the imperfect balance in figure 10(b) is inaudible above the internal receiver noise. The above tests were made using a noise pulse 40 microseconds long at a repetition rate of 10 kcs. This seemed to be about the upper limit for successful blanking with the unit being tested. This fact is attributed to the poor balance characteristics of the particular switching stage used and not to any inherent defect in the basic system. For example, the waveform of figure 9(b) was taken at a repetition rate of 100 kcs. Changing pulse repetition rate, pulse length or shape do not have any appreciable effect on the shape of this waveform. This means that the upper limit on the number of noise pulses which can be rejected will probably depend on how well the switching stage can be balanced for the higher blanking rates.

One limitation of the blanking systems described in this section which must be considered is the possibility of cross modulation occurring in the signal channel. Since the only selectivity

in the system is the broad signal response of the pulse shortening lines, it is highly probable that cross modulation troubles will be encountered when strong local signals lie within the pass band of the system. In order to avoid this trouble it may be necessary to reduce the number of signal amplifier stages to the bare minimum, and design the remaining stages to give the minimum amount of third order distortion. The solution may be to use variable μ tubes or highly degenerative circuits such as the grounded grid amplifier in the signal stages.

In comparing the operation of the blanking system with a standard series type audio limiter[44], the most marked difference is noted at the higher noise reoccurrence rates. At frequencies below 1000 pulses per second the series noise limiter does a very creditable job. As the frequency increases, however, the audio limiter becomes less and less effective until somewhere between 2000 and 3000 p.p.s., depending upon the character of the noise pulses, intelligibility is lost completely. The blanking unit, however, continues to operate effectively up to 10,000 p.p.s.

One of the most striking ways of comparing the two systems is to tune in a broadcast station on a receiver equipped with an audio limiter and couple a pulse generator to the antenna. With the audio limiter on and the blanking unit off, the repetition rate of the pulse generator is increased until the signal is unintelligible. When the

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[44] Wasmansdorf limiter installed in Navy ARB receiver.

blanking unit is cut in the signal stands out and the noise disappears as completely as if the pulse generator were cut off.

IV. CONCLUSION

Noise reducing systems with the complexity of the unit described in the previous section obviously will not be used in receivers where cost must be seriously considered. For some services, however, intelligible communications over widely varying conditions of noise interference is the controlling factor. For this type of service, the complexity and cost of the noise reducing system is unimportant providing the system gives the desired performance.

An important principle in impulse noise reduction is that of reducing the effects of shock excitation in the receiver by placing the noise reducing system as close to the input of the receiver as possible. In the blanking system described in the previous section, this principle is carried to its logical limit by actually placing the noise reducing device ahead of the receiver, thus preventing shock excitation.

Most of the impulse noise reducing systems in use today operate on the amplitude characteristic of the noise pulse. This method imposes a limitation on the performance of the system in that the noise must be stronger than the desired signal before the noise can be detected. Since impulse noise is characterized by steep wave fronts, the method of detecting the noise by its rate of rise rather than by its amplitude characteristics seems fundamentally sound. The "tuned" discriminator described in the previous section is an example of a circuit which operates on this principle. More investigations along these lines will no doubt bring to light other methods of accomplishing the same thing.

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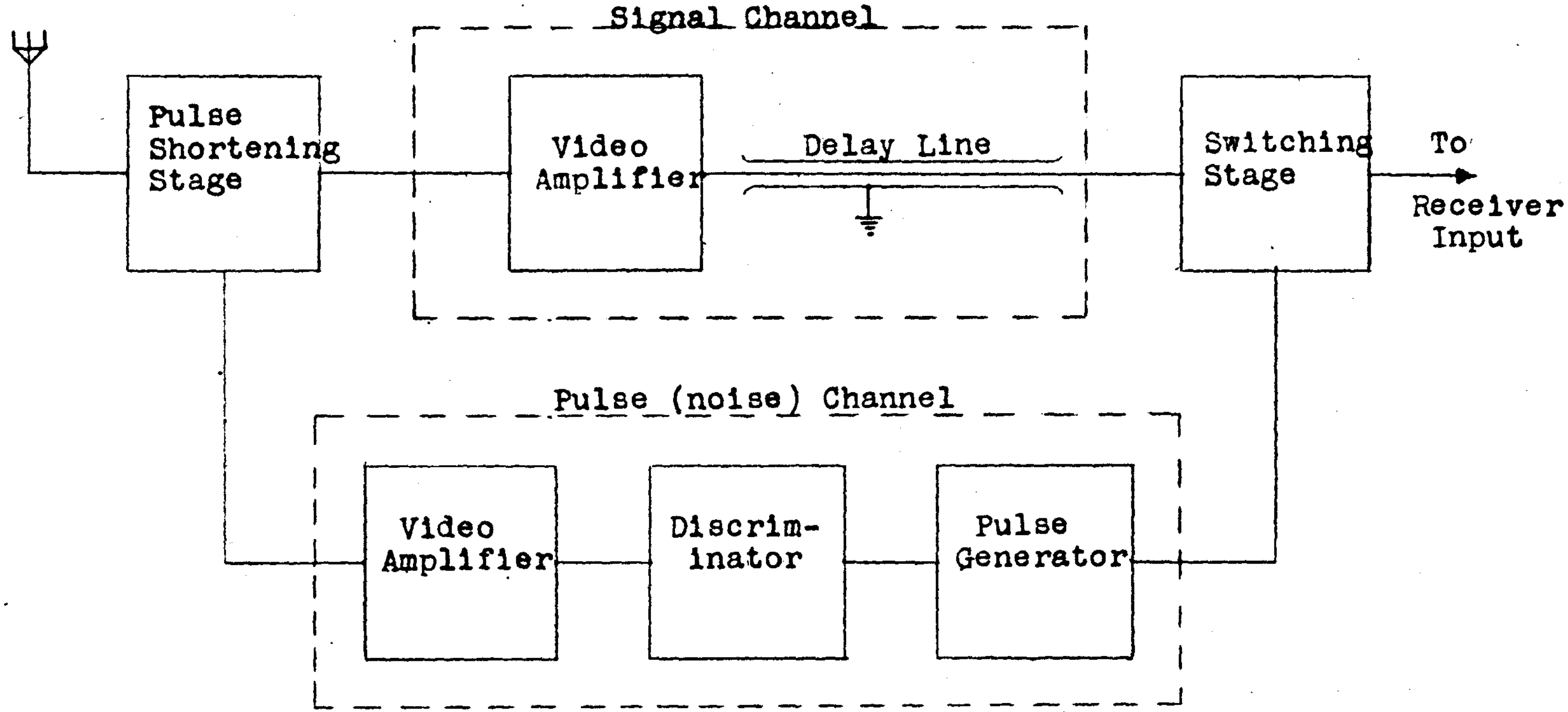
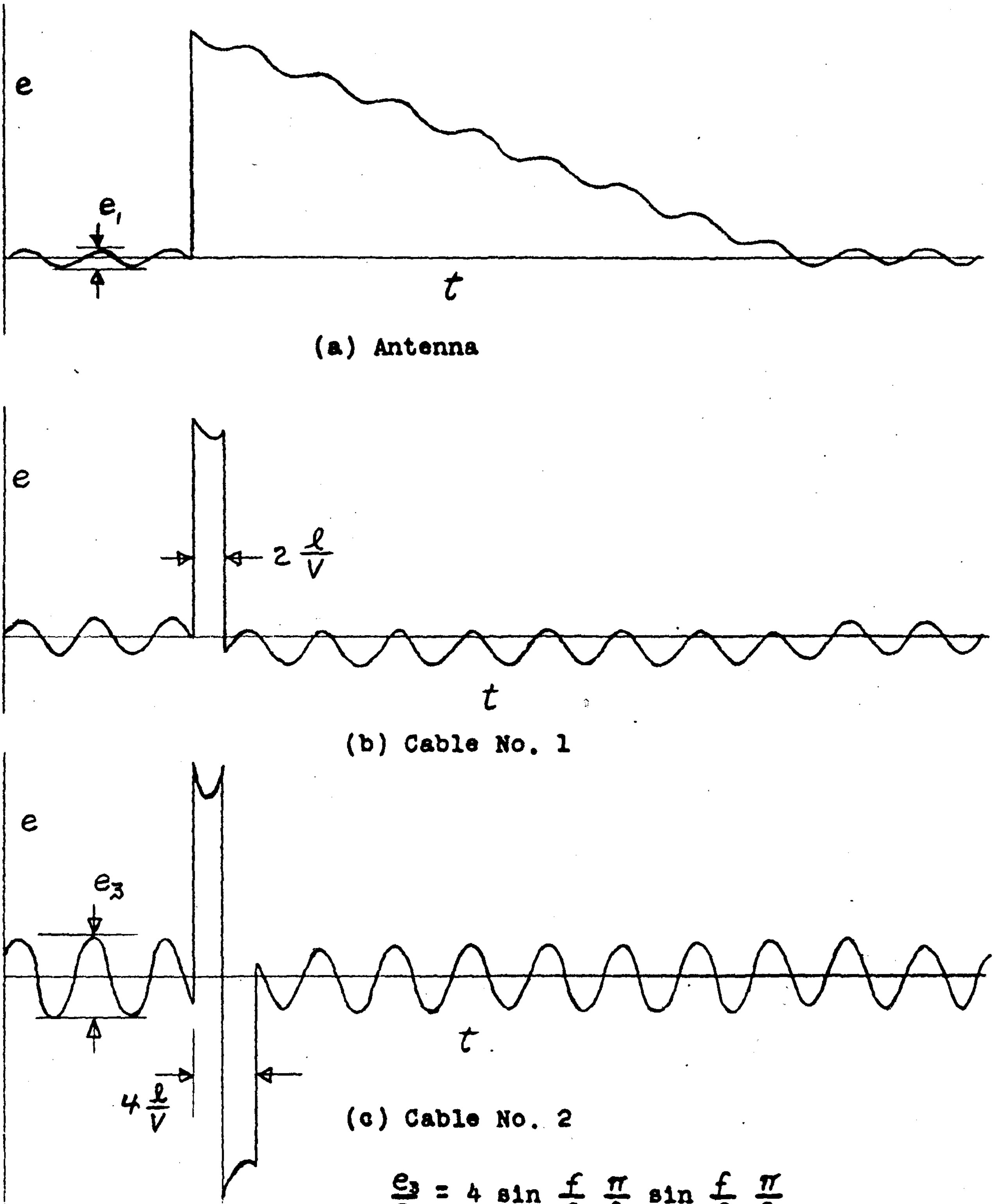
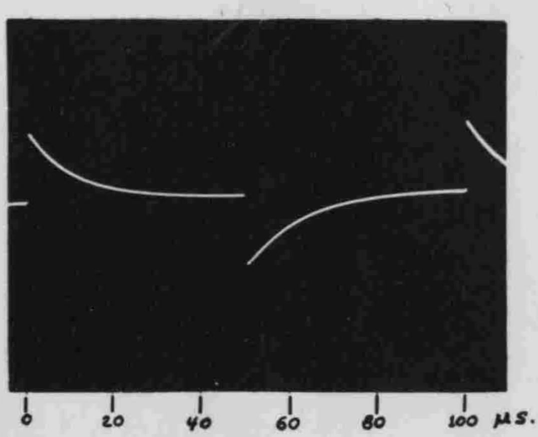


Figure 1. Noise Blanking System

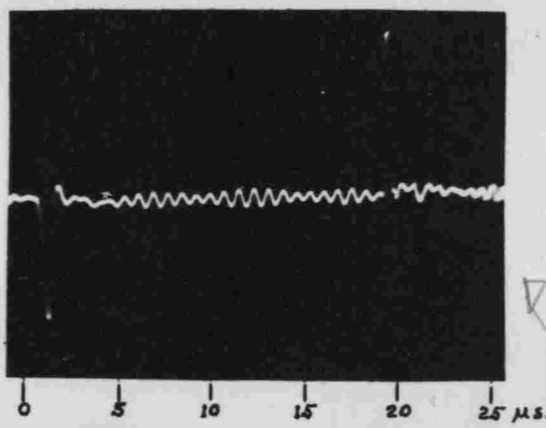


$$\frac{e_3}{e_1} = 4 \sin \frac{f}{f_1} \frac{\pi}{2} \sin \frac{f}{f_2} \frac{\pi}{2}$$

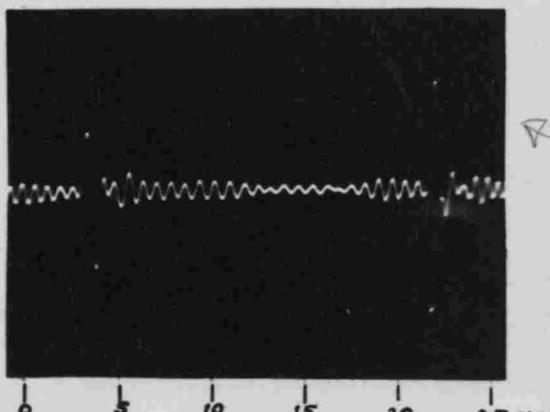
Figure 2. Pulse Shortening and Signal Response.



(a) Noise Pulse on Antenna.



(b) 1st Short Circuited Line.



(c) 2nd Short Circuited Line.

Figure 3. Pulse Shortening Oscillograms.

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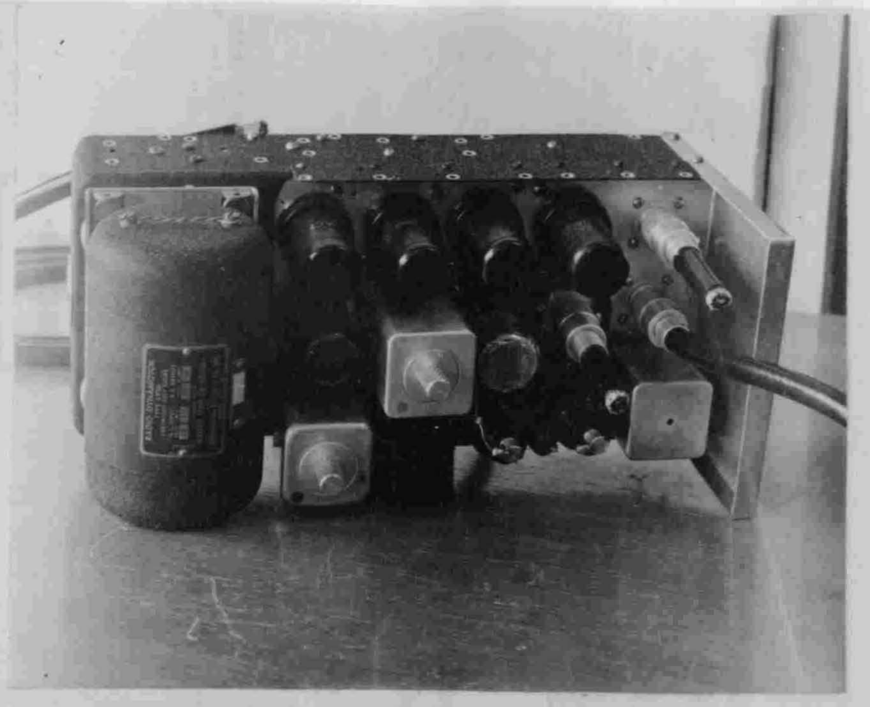
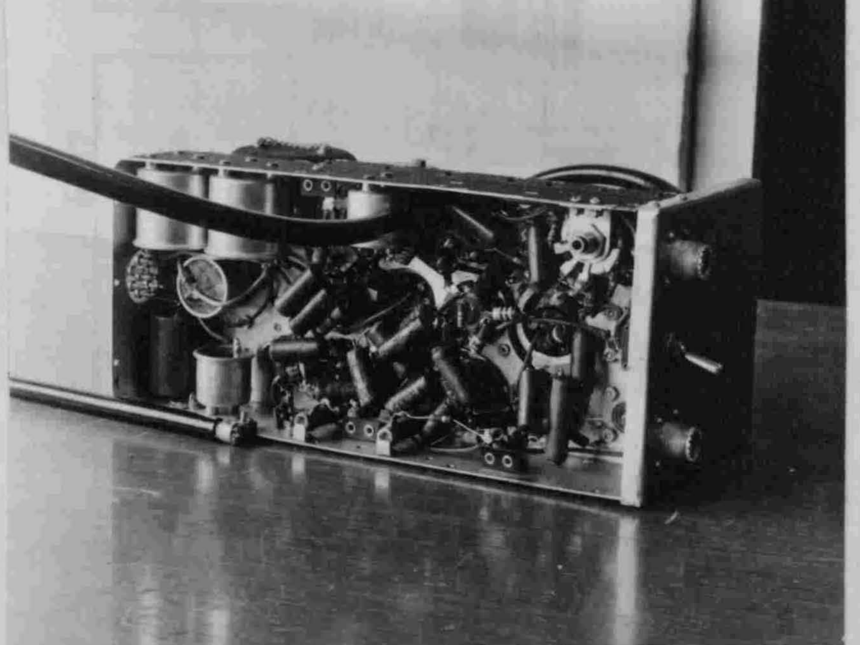


(a) Top View.



(b) Bottom View.

Figure 4. Blanking System Built into Aircraft Type Chassis.

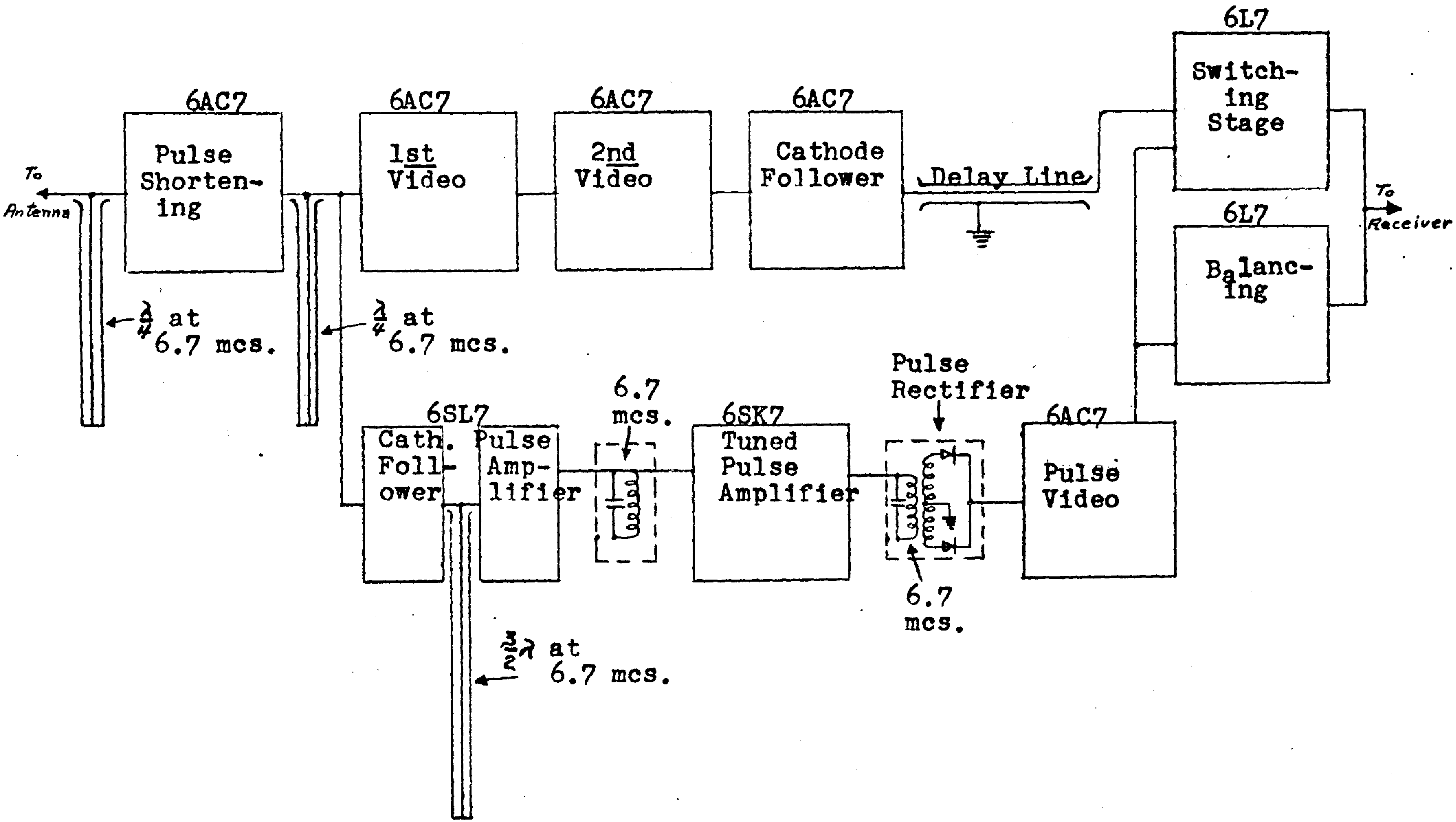


Figure 5. Block Diagram of Modified Blanking System

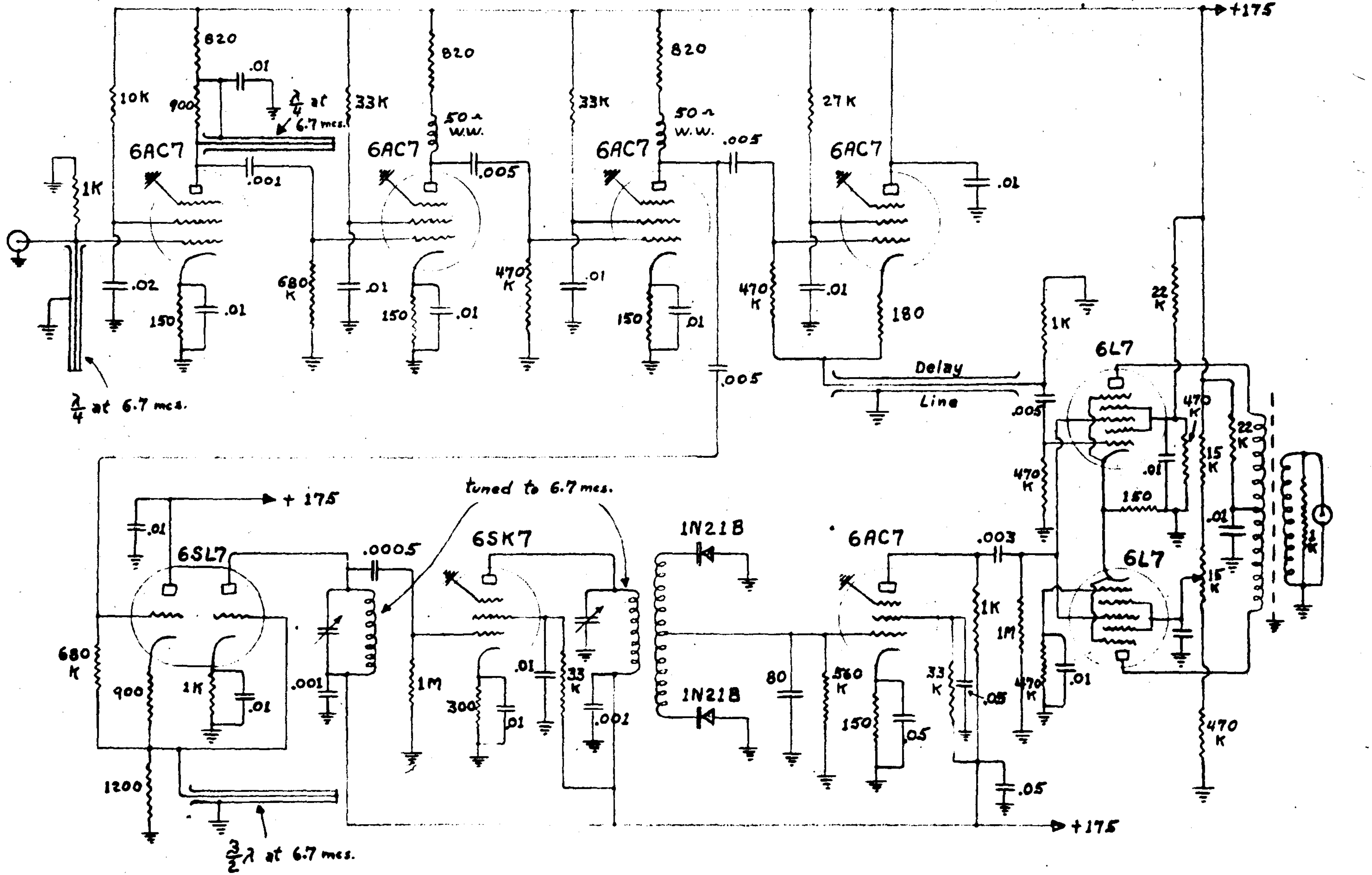


Figure 6. Schematic Diagram of Modified Blanking System.

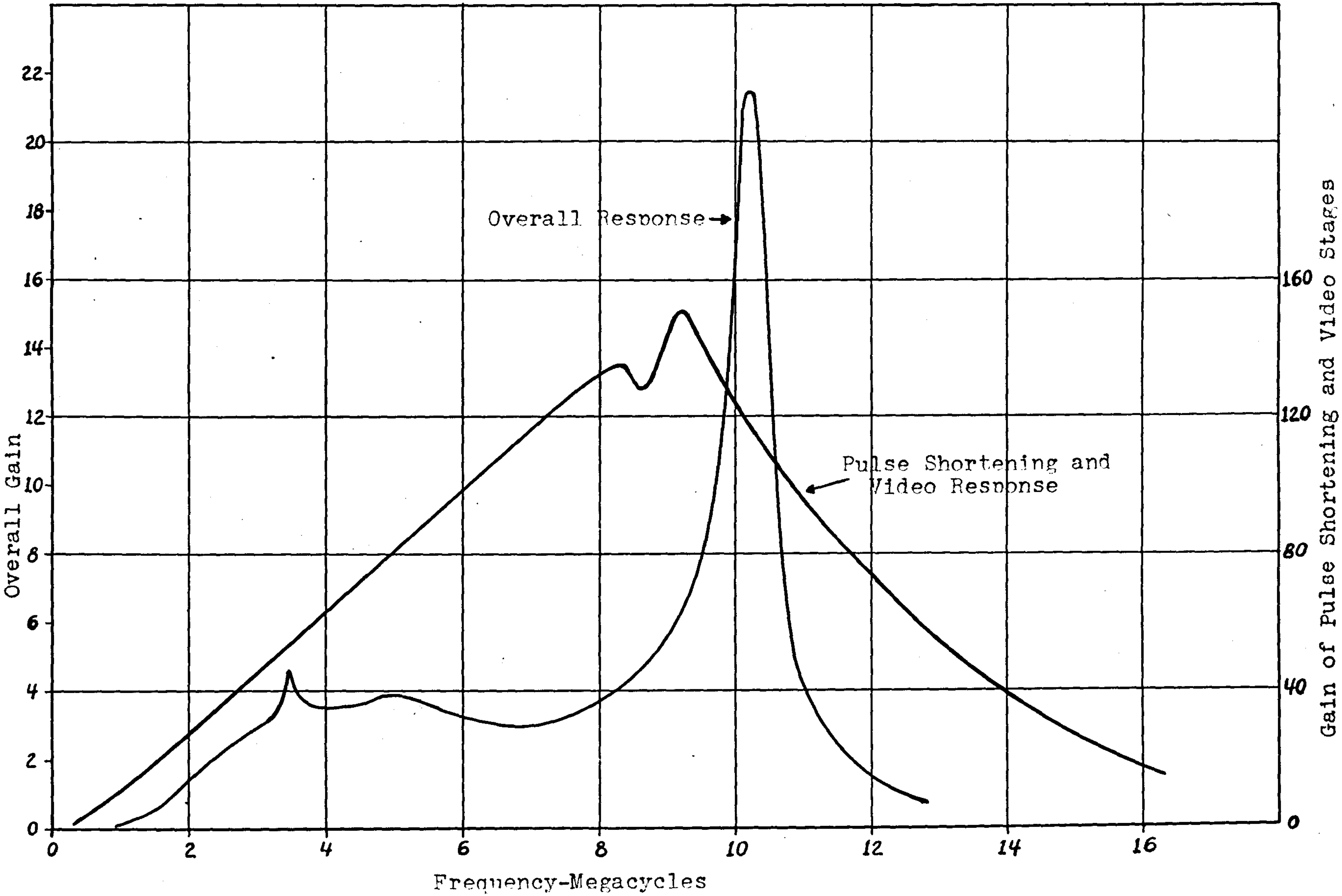
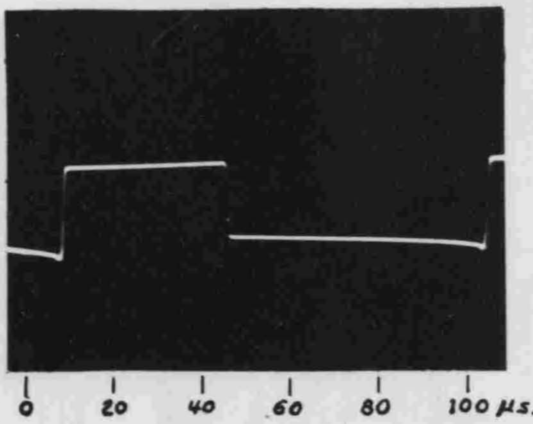
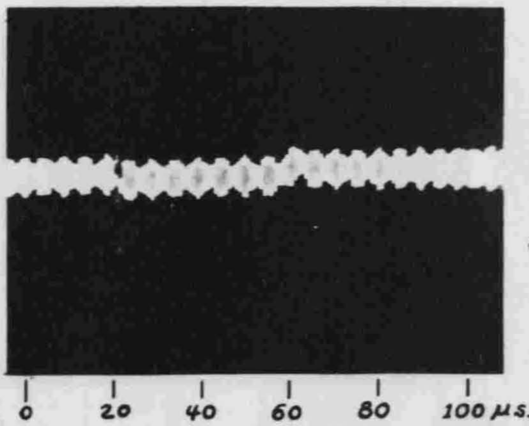


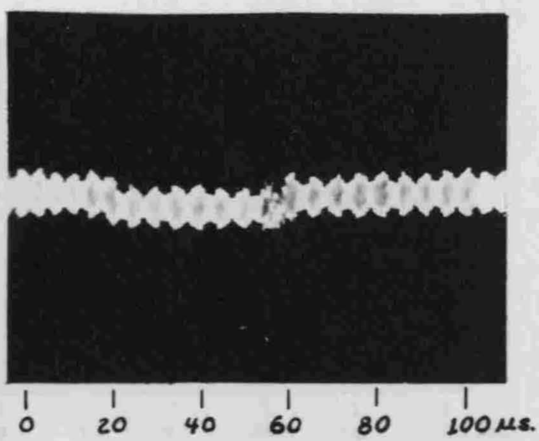
Figure 7. Signal Response of Blanking System



(a) Noise on Antenna.



(b) 1st Short Circuited Line.



(c) 2nd Short Circuited Line.

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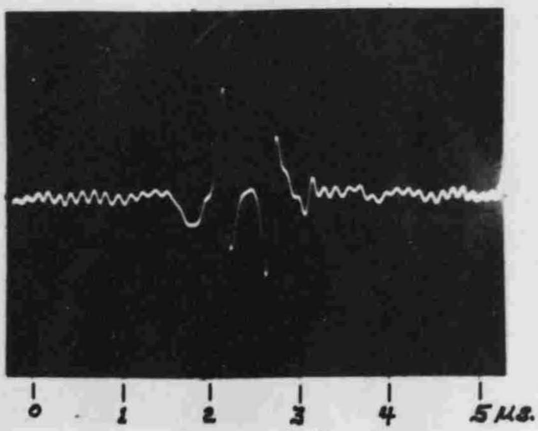
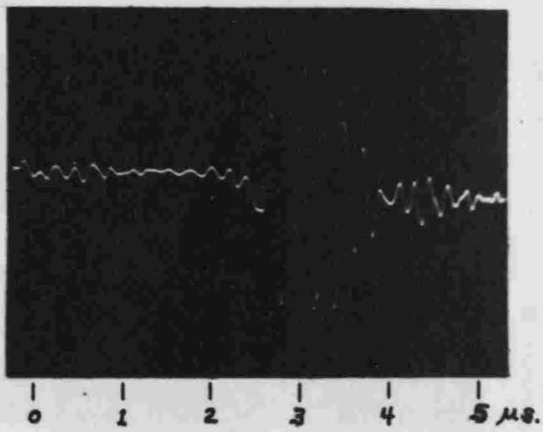
Pulses lost completely in duplication

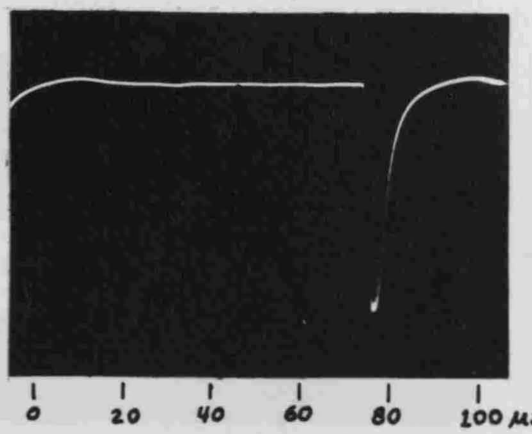
Figure 8. Performance of Modified Blanking System - Pulse Shortening.



(a) Input to Shock Excited Stage.



(b) Plate of Shock Excited Stage.



(c) Blanking Pulse.

Figure 9. Performance of Modified Blanking System-
Disciminator and Pulse Generator.

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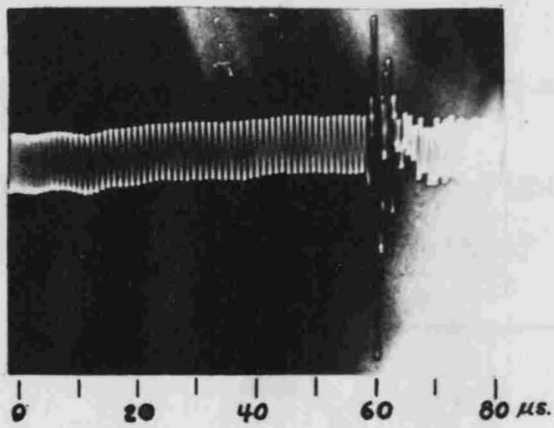
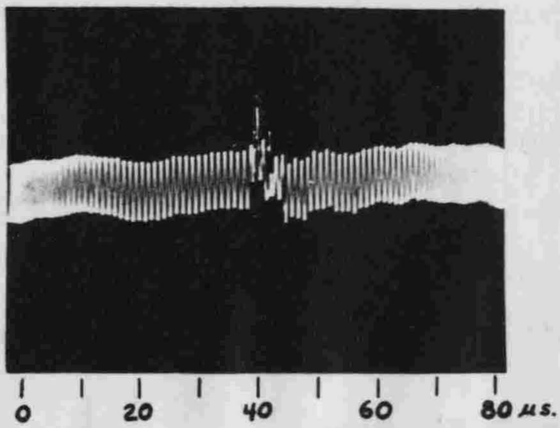
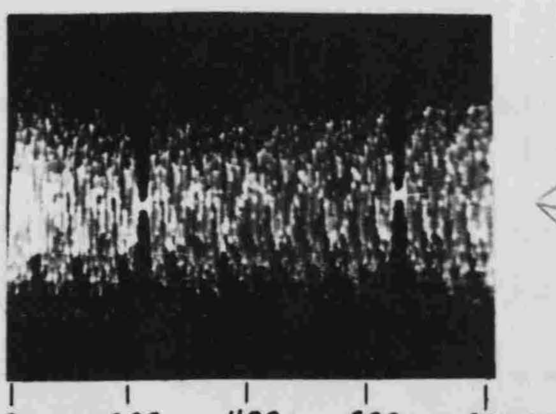


(a) Input to Receiver- No Blanking.



(b) Input to Receiver- With Blanking and Imperfect Balancing.



(c) Input to Receiver- With Blanking and Good Balancing.

Figure 10. Performance of Modified Blanking System- Switching Stage.

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Appendix I

Shock Excitation of a Tuned Circuit as a Function of Rate of Rise of Applied Voltage.

Let the linearly rising voltage of figure 11 be impressed upon the parallel tuned circuit of figure 12.

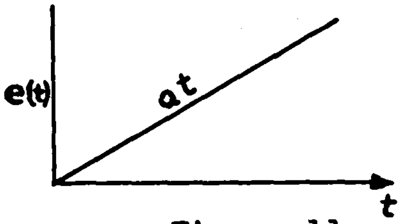


Figure 11

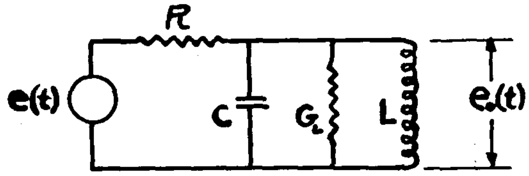
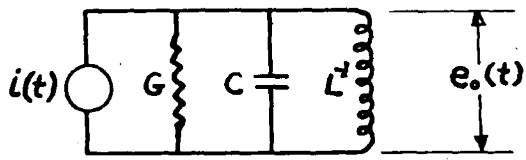


Figure 12

This generalized circuit could, for example, represent the equivalent circuit of a tuned vacuum tube amplifier operating Class A, in which case R would be the plate resistance of the tube and $e(t) = -\mu e_g(t)$, where $e_g(t)$ is the voltage applied to the grid of the tube. Figure 13 is the equivalent single node circuit of figure 12.



where $G = G_L + \frac{1}{R}$

and $i(t) = \frac{e(t)}{R} = \frac{a\,t}{R} u(t)$

Figure 13

In the analysis which follows, the notation used is that of Gardner and Barnes[41].

The integrodifferential equation of figure 13 is

$$e_o(t)\,G + C\frac{de_o(t)}{dt} + \frac{1}{L}\int e_o(t)\,dt = i(t) = \frac{a\,t\,u(t)}{R}$$

---

[41] Gardner, M.F. and Barnes, J.L., Transients in Linear Systems, Vol. I, 1942.

Taking the Laplace transformation of this equation,

$$E_o(s)G + CsE_o(s) - Ce_o(0) + \frac{1}{Ls}E_o(s) + \frac{1}{Ls}e_o^{-1}(0) = \frac{a}{Rs^2}$$

$$\left(G + Cs + \frac{1}{Ls}\right)E_o(s) = \frac{a}{Rs^2} + Ce_o(0) - \frac{1}{Ls}e_o^{-1}(0)$$

$$E_o(s) = \frac{a}{Rs^2\left(G+Cs+\frac{1}{Ls}\right)} + \frac{Ce_o(0)}{\left(G+Cs+\frac{1}{Ls}\right)} - \frac{e_o^{-1}(0)}{Ls\left(G+Cs+\frac{1}{Ls}\right)}$$

$$= \frac{a}{RCs\left(s^2+\frac{G}{C}s+\frac{1}{LC}\right)} + \frac{e_o(0)\,s}{\left(s^2+\frac{G}{C}s+\frac{1}{LC}\right)} - \frac{e_o^{-1}(0)}{LC\left(s^2+\frac{G}{C}s+\frac{1}{LC}\right)}$$

Taking the inverse Laplace transformation,

$$e_o(t) = \frac{a}{RC}\left\{LC + \frac{\sqrt{LC}\,\epsilon^{-\frac{G}{2C}t}}{\sqrt{\frac{1}{LC}-\left(\frac{G}{2C}\right)^2}}\sin\left[\sqrt{\frac{1}{LC}-\left(\frac{G}{2C}\right)^2}\,t - \tan^{-1}\frac{\sqrt{\frac{1}{LC}-\left(\frac{G}{2C}\right)^2}}{-\frac{G}{2C}}\right]\right\}$$

$$+ \frac{e_o(0)\,\epsilon^{-\frac{G}{2C}t}}{\sqrt{LC}\sqrt{\frac{1}{LC}-\left(\frac{G}{2C}\right)^2}}\sin\left[\sqrt{\frac{1}{LC}-\left(\frac{G}{2C}\right)^2}\,t + \tan^{-1}\frac{\sqrt{\frac{1}{LC}-\left(\frac{G}{2C}\right)^2}}{-\frac{G}{2C}}\right]$$

$$- \frac{e_o^{-1}(0)\,\epsilon^{-\frac{G}{2C}t}}{LC\sqrt{\frac{1}{LC}-\left(\frac{G}{2C}\right)^2}}\sin\sqrt{\frac{1}{LC}-\left(\frac{G}{2C}\right)^2}\;t$$

If the initial voltage, $e_o(0)$, on the condenser and the initial current, $\frac{e_o^{-1}(0)}{L}$, in the inductance are small, the last two terms can be dropped, leaving

$$e_o(t) = \frac{aL}{R} + \frac{a\sqrt{LC}\;\epsilon^{-\frac{G}{2C}t}}{RC\sqrt{\frac{1}{LC}-\left(\frac{G}{2C}\right)^2}}\sin\left[\sqrt{\frac{1}{LC}-\left(\frac{G}{2C}\right)^2}\,t - \tan^{-1}\frac{\sqrt{\frac{1}{LC}-\left(\frac{G}{2C}\right)^2}}{-\frac{G}{2C}}\right]$$

If $\frac{1}{LC} >> \left(\frac{G}{2C}\right)^2$, then $\sqrt{\frac{1}{LC}-\left(\frac{G}{2C}\right)^2} \simeq \sqrt{\frac{1}{LC}}$, and

$$e_o(t) \simeq \frac{aL}{R} + \frac{aL}{R}\epsilon^{-\frac{G}{2C}t} \sin\left[\sqrt{\frac{1}{LC}-\left(\frac{G}{2C}\right)^2}\, t - \tan^{-1}\frac{\sqrt{\frac{1}{LC}-\left(\frac{G}{2C}\right)^2}}{-\frac{G}{2C}}\right].$$

The envelope of the oscillation set up in the circuit is $\frac{aL}{R}\epsilon^{-\frac{G}{2C}t}$

The maximum amplitude of oscillation for any given circuit will be proportional to the rate of rise, a , of the applied voltage.

The duration of the wave train produced will be proportional to the Q of the circuit since Q is proportional to $\frac{G}{C}$.

Appendix II

Analysis of Tuned Pulse Amplifier

Figure 14 is the actual circuit to be analysed.

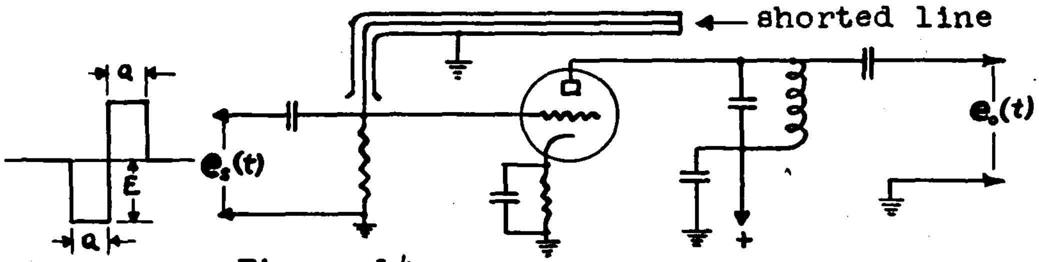


Figure 14.

The equation of the input pulse is

$$e_s(t) = -E\left[u(t) - 2u(t-a) + u(t-2a)\right].$$

Assuming that the reactance of the input and output coupling condensers is negligible, and that the tube is operated over the linear part of its characteristic, the equivalent circuit of figure 15 can be used.

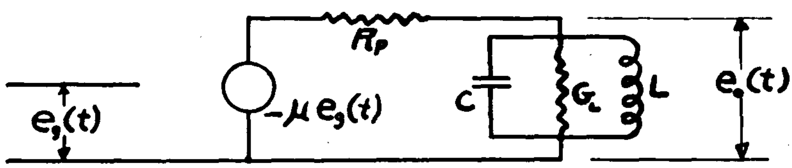
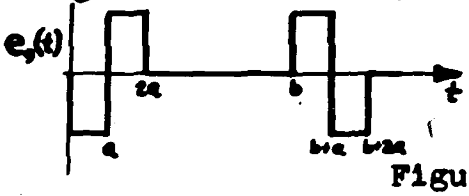


Figure 15.

The series resistance of the inductance is represented by the equivalent parallel conductance, G_L. Strictly speaking, this equivalence is incorrect, but for coils with Q's of 10 or better, the error involved is small enough to justify the substitution.

Because of the negative reflection on the shorted transmission line, the signal applied to the grid, will consist of the input pulse, $e_s(t)$, and the negative of the input pulse, $-e_s(t)$, occurring b seconds later.

Figure 16 is a plot of $e_g(t)$, the signal applied to the grid of the tube.



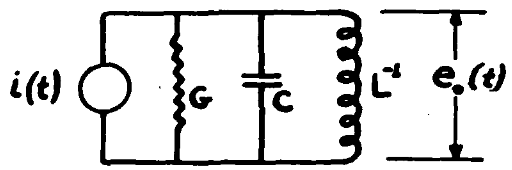
$b = 2\frac{l}{V}$ where l = length of line
V = velocity in line

Figure 16.

The equation of the voltage applied to the grid is

$$e_g(t) = -E\left\{u(t) - 2u(t-a) + u(t-2a) - u(t-b) + 2u[t-(b+a)] - u[t-(b+2a)]\right\}.$$

The equivalent single node circuit is shown in figure 17.



where $i(t) = -\frac{\mu}{R_p} e_g(t)$

$G = G_p + G_L$

$G_p = \frac{1}{R_p}$

Figure 17.

In the solution by Laplace transformation which follows, the notation is that of Gardner and Barnes[42]

The integrodifferential equation of figure 17 is

$$e_o(t) G + C\frac{d e_o(t)}{dt} + \frac{1}{L}\int e_o(t)\,dt = i(t) = -\frac{\mu}{R_p} e_g(t)$$

Taking the Laplace transformation of this equation,

$$E_o(s) G + Cs E_o(s) - Ce_o(0) + \frac{1}{Ls} E_o(s) + \frac{1}{Ls} e_o^{-1}(0) = -\frac{\mu}{R_p} \mathcal{L}[e_g(t)]$$

$$\mathcal{L}[e_g(t)] = -E\left\{\frac{1}{s} - \frac{2\epsilon^{-as}}{s} + \frac{\epsilon^{-2as}}{s} - \frac{\epsilon^{-bs}}{s} + \frac{2\epsilon^{-(b+a)s}}{s} - \frac{\epsilon^{-(b+2a)s}}{s}\right\}$$

$$E_o(s)\left[G + Cs + \frac{1}{Ls}\right] = \frac{\mu E}{R_p}\left[\frac{1}{s} - \frac{2\epsilon^{-as}}{s} + \frac{\epsilon^{-2as}}{s} - \frac{\epsilon^{-bs}}{s} + \frac{2\epsilon^{-(b+a)s}}{s} - \frac{\epsilon^{-(b+2a)s}}{s}\right] + Ce_o(0) - \frac{e_o^{-1}(0)}{Ls}$$

---

[42]Gardner and Barnes, op. cit.

If the initial current in L and the initial charge on C is small, the terms containing $\frac{e_o^{-1}(0)}{L}$ and $e_o(0)$ can be dropped, leaving

$$E_o(s)=\frac{\mu E}{R_p}\frac{\left[\frac{1}{s}-\frac{2\epsilon^{-as}}{s}+\frac{\epsilon^{-2as}}{s}-\frac{\epsilon^{-bs}}{s}+\frac{2\epsilon^{-(b+a)s}}{s}-\frac{\epsilon^{-(b+2a)s}}{s}\right]}{\left(G+Cs+\frac{1}{Ls}\right)}$$

$$=\frac{\mu E}{R_pC}\frac{\left[1-2\epsilon^{-as}+\epsilon^{-2as}-\epsilon^{-bs}+2\epsilon^{-(b+a)s}-\epsilon^{-(b+2a)s}\right]}{\left(s^2+\frac{G}{C}s+\frac{1}{LC}\right)}$$

Taking the inverse of the Laplace transformation,

$$\mathcal{L}^{-1}\left[\frac{1}{s^2+\frac{G}{C}s+\frac{1}{LC}}\right]=\frac{\epsilon^{-\frac{G}{2C}t}}{\sqrt{\frac{1}{LC}-\left(\frac{G}{2C}\right)^2}}\sin\sqrt{\frac{1}{LC}-\left(\frac{G}{2C}\right)^2}\,t$$

Let $\alpha=\frac{G}{2C}$ and $\beta=\sqrt{\frac{1}{LC}-\left(\frac{G}{2C}\right)^2}$, then

$$\mathcal{L}^{-1}\left[\frac{1}{s^2+\frac{G}{C}s+\frac{1}{LC}}\right]=\frac{\epsilon^{-\alpha t}}{\beta}\sin\beta t$$

$$e_o(t)=\frac{\mu E}{R_pC\beta}\Big\{\epsilon^{-\alpha t}\sin\beta t\,u(t)-2\epsilon^{-\alpha(t-a)}\sin\beta(t-a)u(t-a)$$

$$+\epsilon^{-\alpha(t-2a)}\sin\beta(t-2a)u(t-2a)-\epsilon^{-\alpha(t-b)}\sin\beta(t-b)\,u(t-b)$$

$$+2\epsilon^{-\alpha[t-(b+a)]}\sin\beta[t-(b+a)]u[t-(b+a)]-\epsilon^{-\alpha[t-(b+2a)]}\sin\beta[t-(b+2a)]u[t-(b+2a)]\Big\}$$

If $a = \frac{T}{2}$, where $T = \frac{2\pi}{\beta}$ = period of tuned circuit, the first three terms will add up to reenforce the shock excited wave.

If $b = n \cdot 2a = nT$, a cancellation of the wave will result due to the last three terms. Figure 18 shows the resulting wave when $a = \frac{T}{2}$ and $b = 4T$.

Complete cancellation can take place only when $\alpha = 0$. Figure 18 is plotted using this assumption. Actually there will be a residual at $b+2a$ because of the decrement of the circuit.

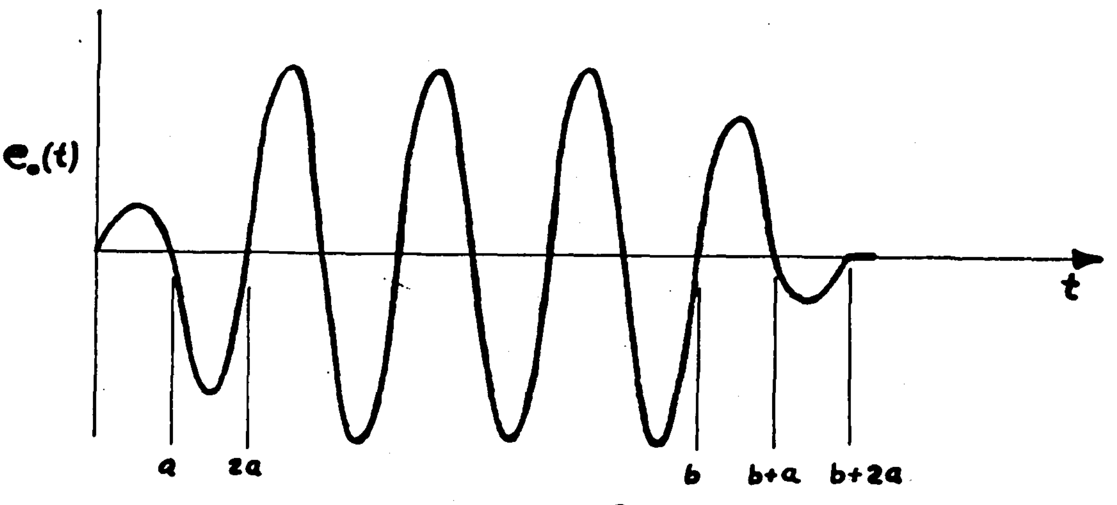


Figure 18.

Appendix III

Cathode Ray Oscillograph used in making Oscillograms

The oscillograms in this report were taken on a cathode ray oscillograph designed and built by the Lightning and Transient Research Laboratory of Minneapolis, Minn. The cathode ray tube is a Dumont 5RP11 and uses a post-deflection accelerating potential of 20 kv. This method of acceleration gives useful writing speeds for photographic work up to 5000 km/sec. Sweep speed is adjustable from 0.1 second to 0.2 microsecond. Either an external or internal signal from vertical deflection channel can be used to trigger the sweep. The vertical deflection channel is equipped with a video amplifier which is flat up to 10 megacycles. The recording camera has an F:1.5 lens and an electrically operated shutter. The film advances automatically when the shutter is closed. Illuminated frame identification numbers of an electromechanical counter are projected onto the cathode ray tube screen and are photographed simultaneously with the trace being recorded. Figure 19 is a photograph of the oscillograph. The camera and viewing hood are mounted so that the screen may be photographed and observed visually at the same time.

Figure 19. Oscillograph used for photographing wave forms.